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COMPLETED PROJECT SUMMARY

1. TITLE: MULTI-INSTRUMENT STUDIES OF THE AURORAL IONOSPHERE

2. PRINCIPAL INVESTIGATOR: Dr. J. C. Foster
M.I.T. Haystack Observatory
Westford, MA 01886

3. INCLUSIVE DATES: 1 November 1985 - 31 October 1988

4. GRANT NUMBER: AFOSR-86-0023

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6. SENIOR RESEARCH PERSONNEL:
Dr. J. C. Foster
Dr. J. M. Holt

7. JUNIOR RESEARCH PERSONNEL:
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Ms. C.-N. Lue
Mr. C. del Pozo

8. PUBLICATIONS:

- Foster, J.C., J.M. Holt, R.G. Musgrove, and D.S. Evans, Ionospheric Convection Associated with Discrete Levels of Particle Precipitation, Geophys. Res. Lett., **13**, 656-659, 1986.
- Foster, J.C., J.M. Holt, R.G. Musgrove, and D.S. Evans, Solar Wind Dependencies of High-Latitude Convection and Precipitation, pp 477-494, Solar Wind-Magnetosphere Coupling, Y. Kamide & J. Slavin, eds., Terra Pub. Co., Tokyo, 1986.
- Ungstrup, G., Heikkila, W.J., Foster, J.C., and Lennartsson, W.O., Compositional Changes, Time and Density Variations in the Magnetosphere Associated with Birkeland Currents and Particle Acceleration, Adv. Space Res., **6**, 113-116, 1986.
- Foster, J.C., Reply to Kamide and Richmond, Geophys. Res. Lett., **14**, 160-161, 1987.
- Mendillo, M., J. Baumgartner, D. Allen, J. Foster, J. Holt, G. Ellis, A. Klekociuk, and G. Reber, Spacelab-2 Plasma Depletion Experiments for Ionospheric and Radio-astronomical Studies, Science, **238**, 1260-1264, 1987.
- Evans, D. S., T. J. Fuller-Rowell, S. Maeda, and J. Foster, Specification of the Heat Input to the Thermosphere From Magnetospheric Processes Using Tiros/NOAA Auroral Particle Observations, Adv. in Astronaut Sci., **65**, 1649-1668, 1987.
- Foster, J. C., Radar-Deduced Models of the Convection Electric Field, pp 71-76, Quantitative Modeling of Magnetosphere-Ionosphere Coupling Processes, Y. Kamide, ed., Kyoto Sangyo Univ. Pub., Kyoto, 1987.

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- Rasmussen, C.E., J.J. Sojka, R.W. Schunk, V.B. Wickwar, O. de la Beaujardiere, J. Foster, J. Holt, Comparison of Simultaneous Chatanika and Millstone Hill Temperature Measurements with Ionospheric Model Predictions, J. Geophys. Res., 93, 1922-1932, 1988.
- Richmond, A.D., Kamide, Y., Ahn, B.H., Akasofu, S.-I., Alcaide, D., Blanc, M., de la Beaujardiere, O., Evans, D.S., Foster, J.C., Friis-Christensen, E., Fuller-Rowell, T.J., Holt, J.M., Knipp, D., Kroehl, H.W., Lepping, R.P., Pellinen, R.J., Senior, C., and Zaitzev, A.N., Mapping Electrodynamical Features of the High-Latitude Ionosphere from Localized Observations: Combined Incoherent-Scatter Radar and Magnetometer measurements for 1984 January 18-19., J. Geophys. Res., 93, 5760-5776, 1988.
- Foster, J. C., C. del Pozo, K. Groves, J.-P. St. Maurice, Radar Observations of the Onset of Current Driven Instabilities in the Topside Ionosphere, Geophys. Res. Lett., 15, 160-163, 1988.
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- St. Maurice, J.-P., J. Foster, J. Holt, and C. del Pozo, First Results on the Observation of 440 MHz High-latitude Coherent Echoes with the Millstone Hill Radar, J. Geophys. Res., 94, 1989.
- Foster, J. C., Plasma Turbulence and Enhanced UHF Radar Backscatter From the Topside Ionosphere, SPI Conference Proceedings Polar Cap Dynamics and High Latitude Turbulence, 8, 1989.
- Foster, J. C., T. Turunen, P. Polari, H. Kohl, and V. B. Wickwar, Multi-Radar Mapping of Auroral Convection, Adv. in Space Res., in press, 1989.
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9. ABSTRACT OF OBJECTIVES AND ACCOMPLISHMENTS:

The MITHRAS data base has been supplemented with the results of coordinated observing campaigns involving satellite and ground-based facilities. Data base and ionospheric modeling techniques have been developed to more fully utilize the multi-instrument data sets. A major objective of this research has been to map the high-latitude ionosphere by combining data from multiple instruments, extending the techniques developed at Millstone Hill under the MITHRAS program. To this end, new data collection modes and analysis techniques were developed which provide good time and spatial coverage and empirical models of the high latitude ionosphere have been developed and tested.

1) The first three-radar azimuth scanning experiment was performed combining observations from Millstone Hill, Sondrestrom, and EISCAT to produce maps of the convection electric field at high latitudes at 30 minute intervals throughout an interval of increasing disturbance.

2) Empirical models of the ionospheric convection electric field were developed from an extensive radar data base. These are keyed to the interplanetary magnetic field and to a new index which quantifies the level and extent of auroral particle precipitation.

3) Quantitative models have been developed describing the distribution of the field-aligned currents which link the ionosphere and magnetosphere at high-latitudes.

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FINAL SCIENTIFIC REPORT

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Massachusetts Institute of Technology

for

AFOSR-86-0023

Multi-Instrument Studies of the Auroral Ionosphere

in

Fiscal Years 1986 - 1988

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distribution unlimited.**

Introduction

The multi-radar MITHRAS experiment and analysis program paved the way for coordinated investigations of the phenomena which couple the high-latitude ionosphere and upper atmosphere to the magnetosphere and solar wind. In the latter half of the 1980's the MITHRAS data base has been supplemented with the results of coordinated observing campaigns involving satellite and ground-based facilities. Data base and ionospheric modeling techniques have been developed to more fully utilize the multi-instrument data sets. This report summarizes the AFOSR-supported analysis activities of the MIT Haystack Observatory Atmospheric Sciences group during the interval November 1, 1985 - October 31, 1988

Research Activities:

The multi-instrument studies begun during the MITHRAS program have been continued in subsequent years making extensive use of the experience and techniques developed in those earlier campaigns. At Millstone Hill the method for deriving electric fields from continuous azimuth scanning experiments was extended to data acquired from the incoherent scatter radars at Sondrestrom, Greenland and EISCAT (Scandinavia). Utilizing the techniques developed under this grant support, multi-radar experiments now produce a time-history of the variation of the convection electric field and other parameters characterizing the ionosphere and thermosphere over a complete span of latitudes from the polar cap to the sub-auroral region.

I) A major objective of this research has been to map the high-latitude ionosphere by combining data from multiple instruments, extending the techniques developed at Millstone Hill under the MITHRAS program.

a) During the grant interval the first three-radar azimuth scanning experiment was performed in December, 1985 (combining observations from Millstone Hill, Sondrestrom, and EISCAT). Direct support of the radar operations at Millstone Hill was provided by the National Science Foundation. Data were received from the three sites in the NCAR data format and convection maps were derived over the combined radar field-of view (Figure 1a) spanning the noon-sector convection convergence region. The derived pattern compares favorably with the Millstone Hill averaged convection model (Figure 1b), also developed under this grant support.

b) As was demonstrated in Figure 1a, the MILFIT analysis program, which derives convection electric field maps from the scanning data, has been upgraded to accommodate data from any radar facility. In addition, MILFIT was upgraded to account for the effect of coherent echo contamination of the Millstone Hill measurements at close ranges.

c) A 24-hour three-radar experiment (funded separately) was organized for November, 1987 to investigate and map ionospheric phenomena at the auroral oval-polar cap boundary over the course of a day. The analysis capabilities, developed under AFOSR support at Millstone Hill, were used to produce maps of the convection electric field at high latitudes at 30 minute intervals throughout an interval of increasing disturbance. Figure 2 (from Foster et al., 1989) presents a snapshot of the convection topology derived from this experimental technique.

d) This work was further extended, in collaboration with researchers at AFGL, to include convection and particle precipitation data obtained during overflights by the HILAT, DE-1, Polar BEAR, and DMSP satellites during the radar experiments. This work has provided a data base for investigating the relationships between the configuration of the convection electric field and ionospheric plasma density

structure and the field-aligned currents and particle fluxes which link the magnetosphere-ionosphere system.

II) The extensive data collected at Millstone Hill during MITHRAS and other operations has been consolidated to produce analytic ionospheric models. A data base binning procedure has been developed and vector and scalar models have been developed and distributed.

a) Empirical models of the ionospheric convection electric field keyed to a new index which quantifies the level and extent of auroral particle precipitation have been prepared and distributed to a number of groups modeling the thermosphere and ionosphere (Foster et al., 1986a).

b) Average convection patterns keyed to the instantaneous condition of the interplanetary magnetic field (IMF) have been developed (Foster et al. (1986b) and extended by combining several years' observations from the Millstone Hill and Sondrestrom radars. These have been distributed as an addendum to the work of Foster et al. (1986b) and extend the previous modeling well into polar cap latitudes. Figure 3 presents these models for toward and away sector IMF conditions with $B_z < 0$.

c) Average models of exospheric temperature as a function of local time, latitude, season, F10.7, and Kp have been generated using data spanning over half a solar cycle (J. Holt, COSPAR meeting report, 1986). These results compare favorably with the MSIS model.

d) Ionospheric models combining incoherent scatter radar data from the North American radar chain observatories (Sondrestrom, Millstone Hill, and Arecibo) have been generated. Predictions of these models for a given set of conditions in local time, latitude, altitude, season, F10.7, and Kp compare favorably with actual observations from the individual sites (Holt, AGU Meeting, 1986).

e) By combining empirical electric field models derived from the Millstone Hill radar data set with ionospheric conductivity models derived from satellite observations of auroral particle precipitation, a set of quantitative models has been developed (Foster et al., 1989b) which describes the high-latitude distribution of the field-aligned currents which link the ionosphere and magnetosphere. Figure 4 displays the magnitude of the field aligned currents into and out of the ionosphere as a function of local time for three disturbance levels.

f) In the local midnight-sector, differences in the ionospheric convection models based on incoherent scatter radar data and those derived from satellite observations (Heppner and Maynard, 1987) have been investigated. The convection observed during individual radar scans was compared with convection observations from DE satellite overflights (Figure 5a) and these results then compared with the predictions of the two averaged models (Figure 5b).

g) The radar-deduced average convection models have been incorporated into larger models developed to specify ionospheric and thermospheric dynamics (Evans et al., 1987; Richmond et al., 1988).

III) Investigations of ionospheric plasma wave growth and associated radar backscatter have been pursued during the course of this grant period. A MIT graduate student supported by this program, Dr. Carlos del Pozo, has recently received his doctorate degree for the analysis of coherent backscatter from the auroral E region. A new class of intense radar backscatter from the topside F region was identified during the grant period.

a) The general characteristics of coherent radar backscatter from E region irregularities as observed with the Millstone Hill UHF radar was the subject of an intensive study which culminated in the report of St. Maurice et al. (1989).

b) The high sensitivity of the Millstone UHF radar was utilized in the dissertation research of Dr. del Pozo to obtain simultaneous coherent echo and incoherent backscatter returns from the E and F region on the same field line. (Antenna sidelobe returns are used for the intense E region echos.) This study

details the relationship of coherent echo occurrence and the characteristics of the ionospheric convection electric field.

c) The work outlined above involved the development of a spectral analysis program to separate the coherent and the incoherent scatter spectra observed by the radar.

d) Intense enhancements of the incoherent scatter spectrum at the local ion acoustic frequency were identified in the topside F region near the ionospheric trough during disturbed conditions (Foster et al., 1988). Radar backscatter from these short-lived plasma waves exhibits many of the characteristics of hard-target backscatter from a satellite or piece of space debris penetrating the radar beam. Figure 6 presents Millstone Hill observations of intense acoustic wave radar echos from topside field lines on the edges of the ionospheric trough.

e) A variety of backscatter spectral signatures has been observed in the vicinity of strong ionospheric currents in addition to the parallel current-induced enhancement of the acoustic line (Foster, 1989).

IV) The ability of the radar observations to quantify ionospheric characteristics was used in a series of comparisons with current ionospheric models. Multi-radar/model case studies which include the effects of high latitude plasma transport were pursued with the goal of improving the detailed ionospheric predictive capability of the models. These model studies have been directed towards reproducing large-scale ionospheric and thermospheric features and their diurnal and activity variation and include satellite as well as radar data as inputs.

a) Plasma data observed during MITHRAS experiments at Millstone Hill and Chatanika have been incorporated with an ionospheric model by Rasmussen et al.(1986) to predict the diurnal evolution of ionospheric density at several latitudes and altitudes.

b) Multi-instrument/model intercomparisons addressed plasma temperatures at high latitudes and the assumptions involved in determining them from the radar data or from the model (Rasmussen et al., 1988).

V) An addendum to this grant supported the analysis and modeling of Millstone Hill observations of the ionospheric hole formed during the 1985 Spacelab-2 experiments. An initial publication providing an overview of this complex event has been prepared (Mendillo et al., 1987). A time history of 40 min period plasma waves, possibly triggered by the event, has been presented in preliminary work by Foster et al., COSPAR Meeting report, 1986).

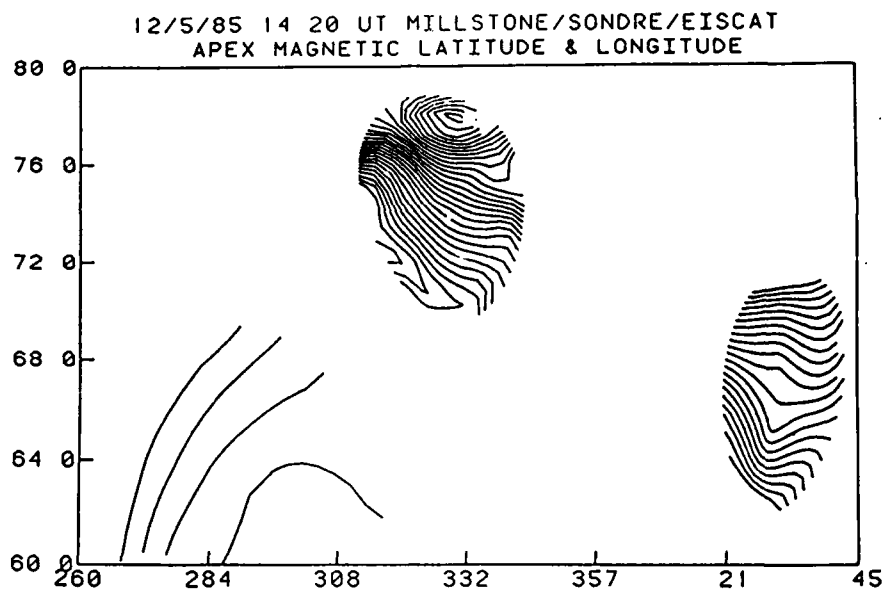


Figure 1a. Convection equipotential contours derived from simultaneous observations with the Millstone Hill, Sondreström, and EISCAT radars.

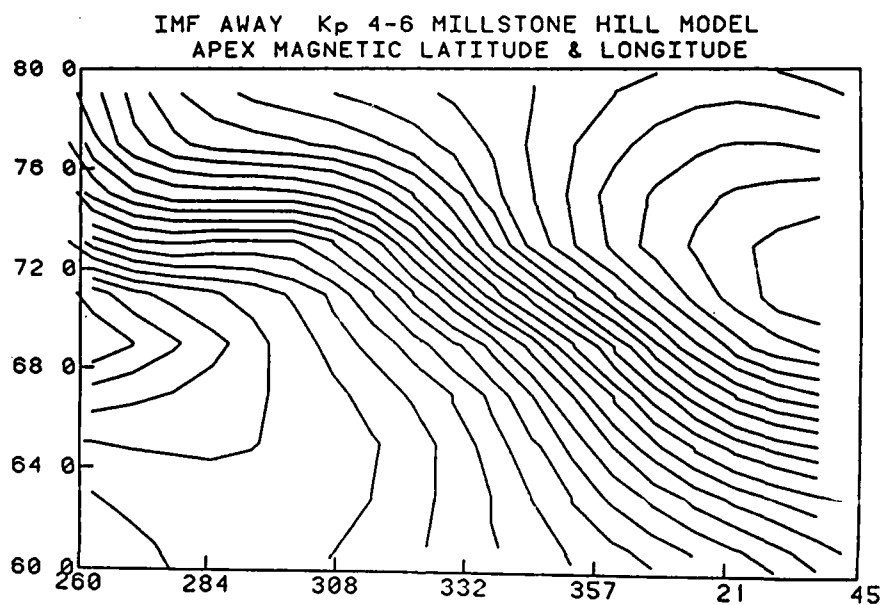


Figure 1b. Convection equipotentials derived from the Millstone Hill average convection model for conditions appropriate to the observations of figure 1a. Model and observations display good qualitative agreement.

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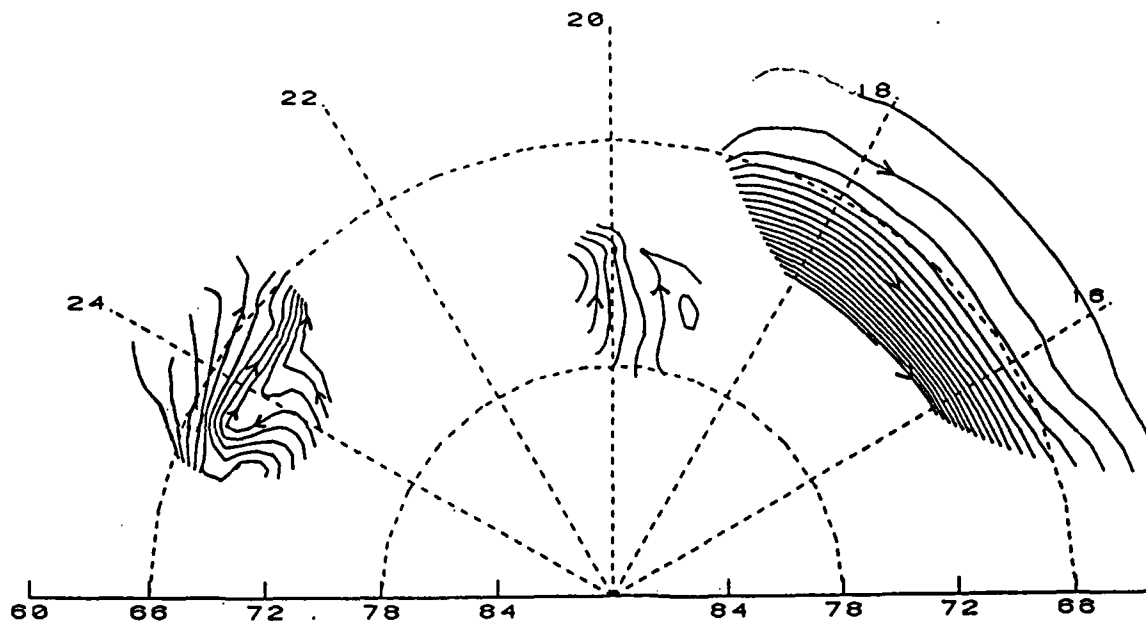


Figure 2. High-latitude ionospheric convection electric field (equipotentials at 2 kV spacing) derived from simultaneous azimuth scans at Millstone Hill, Sondrestrom and EISCAT. The combined radar fields of view span 10 hours of local time.

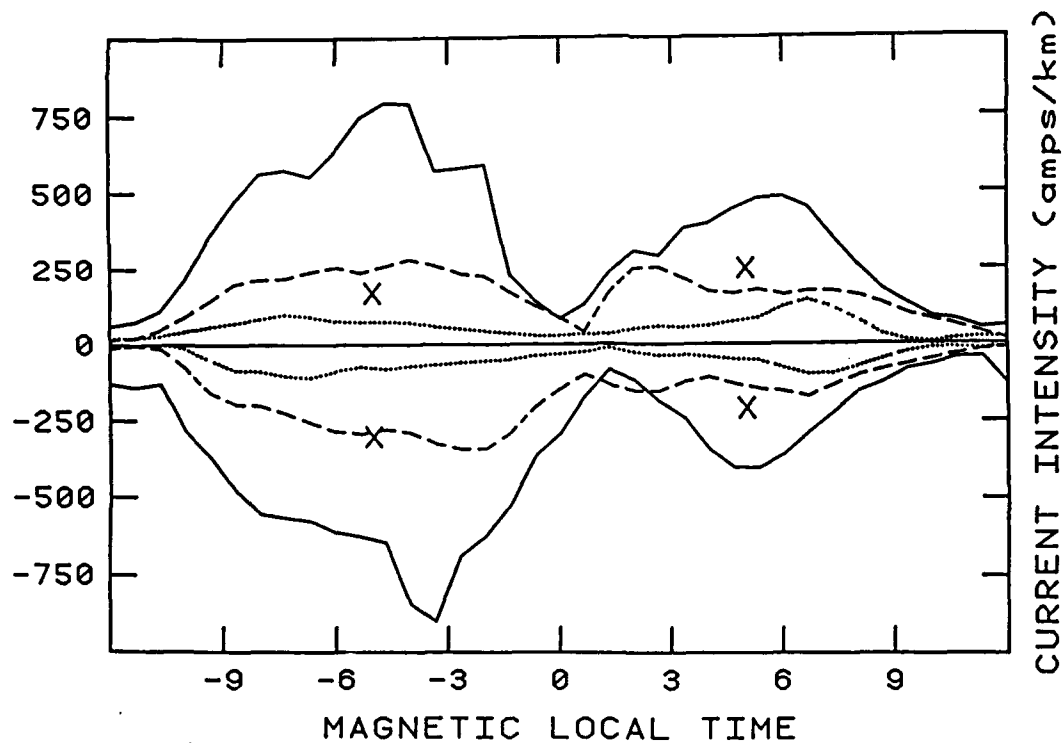


Figure 4. Average field aligned current intensity into (+) and out (-) of the ionosphere at each local time derived from a combined radar/satellite data base. Current intensity for three levels of precipitation activity index are shown.

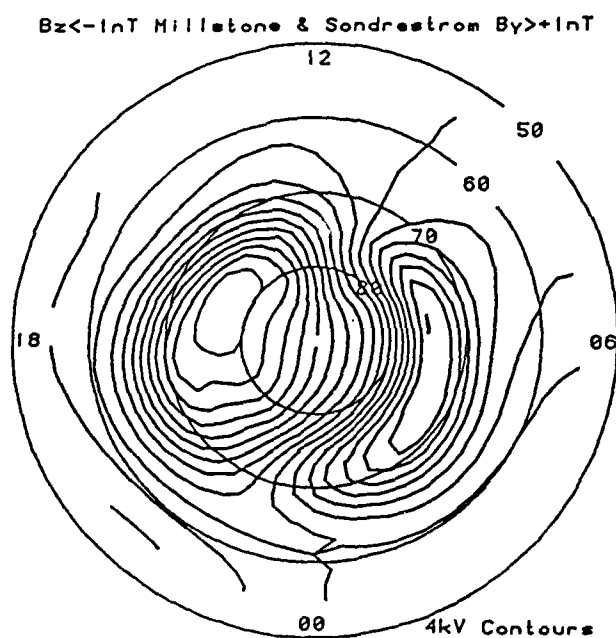
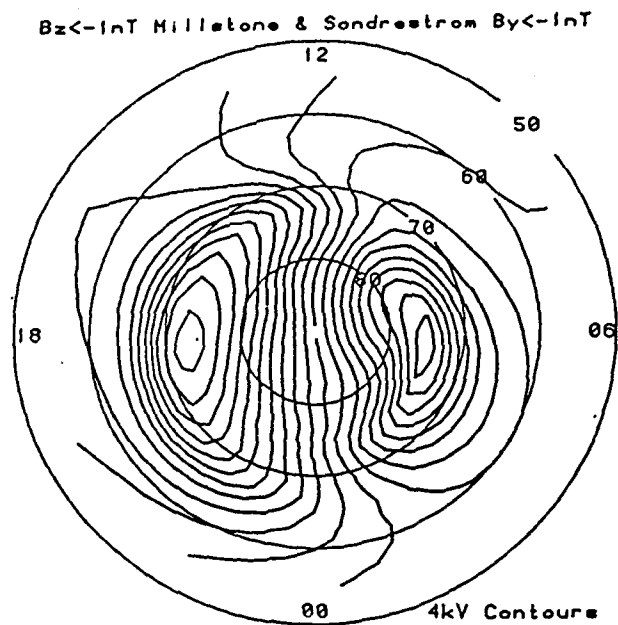


Figure 3. Average models of convection electric field (equipotential contours at 4 kV spacing) derived from a multi-year data base of Millstone Hill and Sondrestrom radar observations of plasma convection are presented for two orientations of the interplanetary magnetic field.

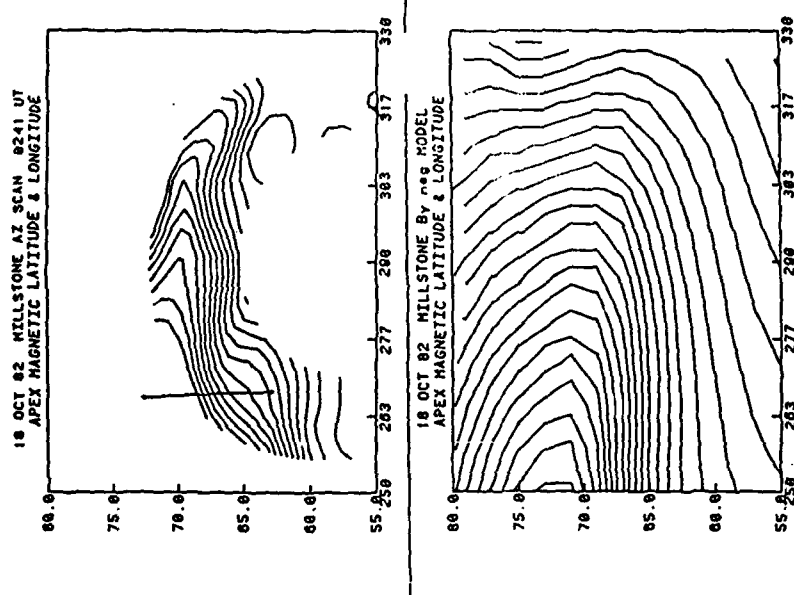


Figure 5b. Convection pattern of fig 2a displayed in magnetic lat/lon coordinates (top). Millstone convection model (bottom) displayed in a similar format. The gross convection features are well represented by the model.

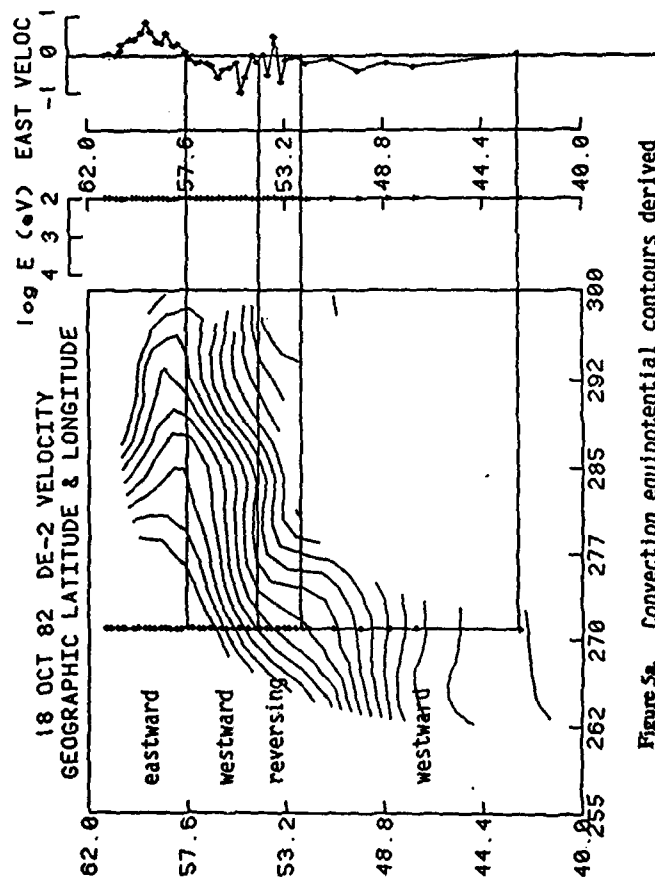


Figure 5a. Convection equipotential contours derived from a single azimuth scan with the Millstone Hill radar are used to map the ionospheric convection in the midnight sector. East-west plasma drift velocity observations made during an overflight of the Dynamics Explorer satellite are superimposed (the sub-satellite track is plotted). The radar map details the spatial extent of the convection pattern.

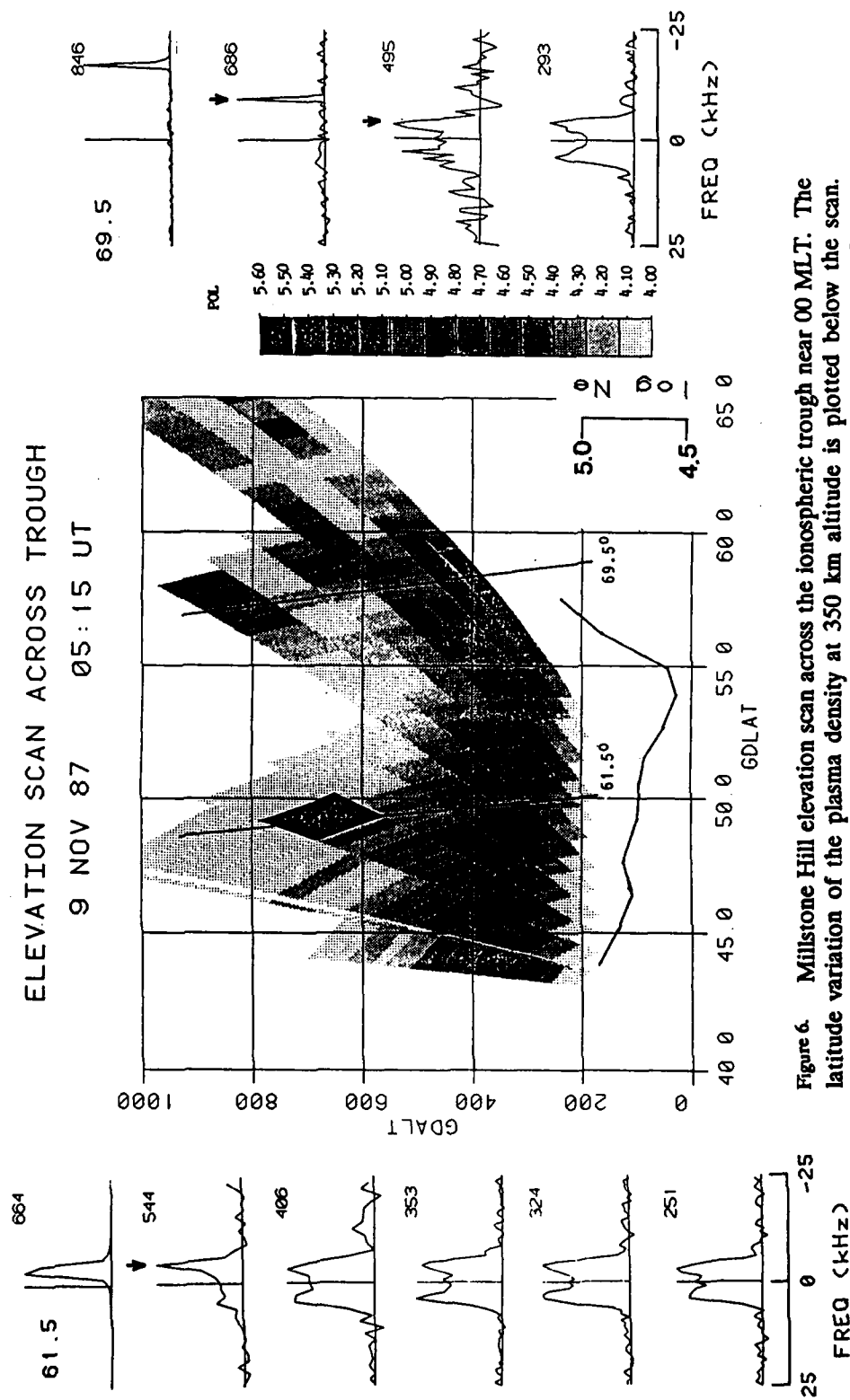


Figure 6. Millstone Hill elevation scan across the ionospheric trough near 00 MLT. The latitude variation of the plasma density at 350 km altitude is plotted below the scan. Backscatter is enhanced by a factor of 100 on the equatorward edge of the trough. Spectra observed along field lines intersecting regions of topside backscatter power enhancement at the equatorward and poleward edges of the trough are shown to the left and right, respectively. The ion acoustic frequency is indicated at 495 km and 544 km altitude and the ion plasma frequency is shown at 686 km.

Research Papers Generated under AFOSR Support

Cumulative: FY '86 - FY '88

- Foster, J.C., J.M. Holt, R.G. Musgrove, and D.S. Evans, Ionospheric Convection Associated with Discrete Levels of Particle Precipitation, Geophys. Res. Lett., **13**, 656-659, 1986.
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- St. Maurice, J.-P., J. Foster, J. Holt, and C. del Pozo, First Results on the Observation of 440 MHz High-latitude Coherent Echoes with the Millstone Hill Radar, J. Geophys. Res., **94**, 1989.
- Foster, J. C., Plasma Turbulence and Enhanced UHF Radar Backscatter From the Topside Ionosphere, SPI Conference Proceedings Polar Cap Dynamics and High Latitude Turbulence, **8**, 1989.
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Travel Supported by AFOSR Project

December, 1985, San Francisco, Ca.: J. Foster to attend Fall Annual Meeting of AGU (2 papers presented).

May, 1986, Baltimore, Md.: J. Foster and C. del Pozo to attend Spring Annual Meeting of AGU (2 papers presented).

June, 1986, Boulder, Co.: J. Foster to attend Multi-Radar/CEDAR Meeting (discussed multi-radar campaigns and analysis projects).

July, 1986, Toulouse, France: J. Holt to attend XXVI Meeting of COSPAR (2 papers presented).

December, 1986, San Francisco, Ca.: J. Foster to attend Fall Annual Meeting of AGU (paper presented).

May, 1987, Baltimore, Md.: J. Foster to attend Spring Annual Meeting of AGU (discussed multi-radar campaigns and analysis projects).

August, 1987, Vancouver, B.C.: J. Foster to attend IAGA Symposium (paper presented).

November, 1987, Williamsburg, Va.: J. Foster to attend SUNDIAL Workshop (multi-radar experiment workshop).

March, 1988, Washington, D.C.: J. Foster for discussions and to present seminar at AFOSR.

May, 1988, Baltimore, Md.: J. Foster to attend Spring Annual Meeting of AGU (paper presented).

July, 1988, Helsinki, Finland: J. Foster to attend COSPAR meeting (two papers presented).

October, 1988, Washington, D.C.: J. Foster for discussions at AFOSR.

Professional Personnel

Dr. J. C. Foster - Principal Investigator

Dr. J. M. Holt - co-Principal Investigator

Dr. A. P. van Eyken (during period 11/86-4/87)

Dr. D. X. Tetenbaum (during period 4/87-10/88)

Ms. C.-N. Lue (applications programming)

Mr. C. del Pozo - MIT graduate research assistant

Scientific Interactions

1. Spoken Papers:

- Multi-radar Mapping of the High-latitude Ionosphere, (J. Foster), US-Finland Auroral Workshop, Sodankyla, Oct., 1985 (invited).
- Average Patterns of High-latitude Ionospheric convection derived for fixed levels of Precipitating Particle Energy Input (J. Foster, J. Holt, R. Musgrove and D. Evans), AGU, San Francisco, December, 1985.
- Radar/Satellite Studies of the Auroral Oval - Polar Cap Boundary (J. Foster, and D. Evans), AGU, San Francisco, December, 1985.
- Ionospheric Convection Associated with Discrete Levels of Particle Precipitation (J. Foster, J. Holt, R. Musgrove, and D. Evans), AGU, Baltimore, May, 1986.
- Phase Velocity and Electric Field Dependencies for 30 cm Auroral E-region Irregularities (C. del Pozo, and J. Holt), AGU, Baltimore, May, 1986.
- Radar-Optical Observations of the Spacelab-2 Plasma Depletion Experiments over Millstone Hill, (J. Foster, J. M. Holt, W. L. Oliver, M. Mendillo, and J. Baumgartner), XXVI Meeting of COSPAR, Toulouse, July, 1986.
- Empirical Models for Exospheric Temperature Between 24 and 60 deg N from Millstone Hill Observations, (J. Holt and R. Musgrove), XXVI Meeting of COSPAR, Toulouse, July, 1986.
- Empirical Ionospheric and Thermospheric Models from Incoherent Scatter Radar Chain Data, (J. M. Holt), Fall Annual Meeting of the American Geophysical Union, San Francisco, Dec., 1986).
- Height and Aspect Angle Studies of Backscatter from 30 cm Auroral E-region Irregularities, (J.C. Foster, and C. del Pozo), AGU, San Francisco, December, 1986).
- Field Aligned Current Distribution in the Auroral Ionosphere, (J.C. Foster, T. Fuller-Rowell, and D.S. Evans) AGU Fall Meeting, San Francisco, CA, December, 1986).
- Analytic Models of High-latitude Ionospheric Electrodynamics, International Symposium on Large-scale Processes in the Ionospheric-Thermospheric System, (J.C. Foster) Boulder, Dec., 1986).
- Coherent Radar Backscatter from Topside F-Region 30 cm Irregularities Associated with the Ionospheric Trough, (J.C. Foster, J.M. Holt, and C. del Pozo) IAGA Symposium, Vancouver, Canada, August 1987).

Empirical Ionospheric and Thermospheric Models from Incoherent Scatter Radar Chain Data, (J.M. Holt) presented at the International Symposium on Large-Scale Processes in the Ionospheric-Thermospheric System, December, 1986).

Radar-deduced Models of the Convection Electric Field (J. C. Foster), International Symposium on Quantitative Modeling of Magnetospheric-Ionospheric Coupling Processes, Kyoto, Japan, March, 1987.

The Role of Plasma Convection in the Formation of the Evening Sector Ionospheric Trough (J. C. Foster), IAGA Symposium, Vancouver, Canada, August, 1987.

Coherent Radar Backscatter from Topside F-Region 30 cm Irregularities Associated with the Ionospheric Trough (J. C. Foster, J. M. Holt, and C. del Pozo), IAGA Symposium, Vancouver, Canada, August 1987.

Equipotential Contours and Charged Particle Boundaries in the Pre-midnight Sector: A Composite from DE and Millstone Hill (J. C. Foster, P. F. Bythrow, N. C. Maynard, J. D. Winningham), Fall Annual Meeting of AGU, San Francisco, Dec. 1987.

Intense UHF Radar Backscatter from the Topside Ionosphere (J. C. Foster, 1988 Space Surveillance Workshop, MIT Lincoln Laboratory, April 1988.

UHF Radar Backscatter From Irregularities Associated with a Critical Layer in the Topside F Region (J. C. Foster, C. del Pozo, K. M. Groves), Spring Annual Meeting of AGU, Baltimore, 1988.

Intense Radar Backscatter and Current Driven Instabilities in the Topside Ionosphere (J. C. Foster), 1988 Cambridge Workshop on Polar Cap Dynamics and High Latitude Ionospheric Turbulence, 1988.

Radar Observations of the Onset of Current-Driven Instabilities in the Topside Ionosphere (J. C. Foster, C. del Pozo, K. Groves, J. -P. St. Maurice), XXVII Cospar - Espoo, Finland, July 1988.

Multi-Radar Mapping of Auroral convection (J. C. Foster), XXVII Cospar - Espoo, Finland, July 1988.

Plasma Transport through the Dayside Cleft: A Source of Ionization Patches in the Polar Cap (J. C. Foster), Nato Advanced Research Workshop on Electromagnetic Coupling in the Polar Clefts and Caps, Lillehammer, Norway, Sept. 1988.

Two-Dimensional Mapping of Dayside Convection, Nato Advanced Research Workshop on Electromagnetic Coupling in the Polar Clefts and Caps (J. C. Foster, H. -C. Yeh, J. M. Holt, D. S. Evans), Lillehammer, Norway, Sept. 1988.

High Temporal Resolution Observations of the Convection Reversal Boundary from Millstone Hill (J. C. Foster, J. M. Holt, H. -C. Yeh), Fall Annual Meeting of AGU, San Francisco, Dec. 1988.

2. Consultative and Advisory Functions:

- a) Calibration of AFGL ionospheric model based on Polar BEAR UV imager data (Feb.-March, 1987).
AF/AFGL personnel: J. Jasperse, D. Decker.
- b) Analysis of electric fields for equinox thermospheric weather campaign (Feb.-May, 1987). AF/AFGL personnel: H. Carlson.
- c) Comparison of Millstone Hill radar scan maps with DE-1 and DMSP overflights (April-Oct., 1987).
AF/AFGL personnel: P. Bythrow, N. Maynard.
- d) Calibration of AFGL ionospheric model based on Polar BEAR UV imager data (July-Aug., 1987).
AF/AFGL personnel: R. Huffman, F. del Greco, D. Decker.